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An ecoprofile of thermoplastic protein derived from blood meal Part 2: thermoplastic processing

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Abstract
Purpose The purpose of this research was to develop a nonrenewable energy and greenhouse gas emissions ecoprofile of thermoplastic protein derived from blood meal (Novatein thermoplastic protein; NTP). This was intended for comparison with other bioplastics as well as identification of hot spots in its cradle-to-gate production. In Part 1 of this study, the effect of allocation on the blood meal used as a raw material was discussed. The objective of Part 2 was to assess the ecoprofile of the thermoplastic conversion process and to compare the cradle-to-gate portion of the polymer's life cycle to other bioplastics.
Methods Inventory was collected to aggregate nonrenewable primary energy use and greenhouse gas emissions. Data were collected from a variety of sources including published papers, reports to government agencies, engineering models and information from a single blood meal production facility. Several assumptions regarding the thermoplastic conversion process were evaluated by way of a sensitivity analysis.
Results The allocation procedure chosen for the impacts of farming and meat processing had the greatest effect on results. Excluding farming and meat processing, blood drying had the greatest contribution to nonrenewable energy use and GHGs, followed by the petrochemical plasticizer used. Other assumptions, such as scarcity of water or inclusion of pigments, although significant when considered for blood meal conversion to NTP alone, were found not to be significant when production of blood meal was included in the analysis. Qualitative differences were observed between NTP and other bioplastics. For example, the profiles of some other bio-based polymers were dominated by fermentation and polymer recovery processes. In the case of NTP, it is the production of the raw material used that is most significant, and thermoplastic modification has a relatively low contribution to GHGs and nonrenewable energy use.
Conclusions For a truly attributional scenario, production of any ruminant animal products does have an associated GHG. Deriving this for blood meal on a mass-based allocation seems to indicate that NTP is less favorable than other cradle-to-gate bioplastic production systems from a global warming perspective.

On the other hand, the motivation for developing the material in the first place was to make use of an existing waste product. If it is assumed that the magnitude of blood meal production is independent of fertilizer or plastics demand and, instead, reflects demand for major products such as meat, further development of NTP is justified.

Keywords Allocation · Bioplastic · Blood meal · Cradle to gate · Greenhouse gas emissions · Life cycle assessment · Modified natural polymer · Sensitivity analysis

1 Introduction

In Part 1 of this study, it was reported that blood meal from the meat processing industry can be used as a feedstock to produce bio-based thermoplastic polymers (commonly known as bioplastics). It was also shown that nonrenewable energy use and greenhouse gas emissions (GHGs) attributed to producing blood meal depend on the allocation method used for the multifunctional processes of farming and meat processing. Here, in Part 2, the discussion is extended to the production of non-blood meal additives and processing of

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these together with blood meal to manufacture Novatein thermoplastic protein (NTP). The purpose of this was to arrive at a cradle-to-gate ecoprofile for the production of NTP and compare this to the production of other bio-based plastics. The development of new materials from renewable feedstocks is motivated by environmental concerns. These include dependence on and use of nonrenewable fossil fuels, as well as the contribution of GHGs to global climate change. It is important that environmental impacts of any such materials are evaluated for their performance in addressing the concerns that motivate their development. Life cycle assessment has been applied to other bio-based polymers to assess their contributions to environmental impacts. Both complete cradle-to-grave analyses and partial assessments looking at a cradle-to-gate basis have been used to evaluate bio-based polymers (Madival et al. 2009; Vink et al. 2003).

In polymers manufactured by fermentation of biomass such as sugars or vegetable oils, the fermentation and recovery process are particularly energy intensive. When using conventional energy, these processes contribute to the majority of the nonrenewable primary energy (NRPE) demand and are the primary contributor to most environmental impacts (Akiyama et al. 2003; Gerngross 1999; Kim and Dale 2005).

An alternative to using fermentation processes to produce polymers is to use biomass that already contains biological polymers and modify these to exhibit thermoplastic properties. Thermoplastic starch is commercially available for a number of applications, and its use to displace petroleum-derived plastics has been shown to produce energy savings (Patel 2003a). Energy is still used in crop production and starch extraction, but there is no energy intensive fermentation step. A number of life cycle assessment studies of starch materials have been conducted by manufacturers of these materials in Europe, and summaries of the findings can be found in review chapters in books (Patel 2003a, 2005; Rudnik 2008).

Unlike polyhydroxyalkanoate (PHA) and polylactide (PLA), where much of the work has focused on different production technologies, for starch, there is a body of work considering different end-of-life disposal options. Although some deal with products, some also deal with materials that could be used for a number of applications (Patel 2005). Such analyses could potentially be defined as “cradle to gate plus grave” assessments. This highlights that the biodegradability of starch-based materials is just as much of a motivation for their use as its renewability.

Other natural polymers including polysaccharides, such as cellulose and chitin, as well as proteins can also be converted to thermoplastic materials. To process proteins thermoplastically, noncovalent interactions between chains or different parts of the same chain need to be overcome without damage to the covalent linkages in the amino acid chain. This requires a way to overcome the thermodynamic barriers of chain unfolding, without heating to a temperature where the chains undergo thermal decomposition. As with starch, the addition of selected chemicals can be used to plasticize proteins. Small molecules tend to bind preferentially to the portions of the polypeptide chain that interact with other chains, disrupting the intermolecular interactions. This increases chain mobility and reduce the glass transition to temperatures lower than those where the polypeptide backbone degrades (Verbeek and van den Berg 2010).

Thermoplastic materials derived from proteins are yet to be commercialized on a large scale (Rudnik 2008).

2 Methodology

2.1 Goal definition

As outlined in Part 1, a cradle-to-gate study was conducted with the following objectives:

- To estimate primary energy and GHGs data on the production of NTP in a New Zealand (NZ) context.
- To identify the most significant contributions to impacts on a cradle-to-gate basis.
- To compare with cradle-to-gate production of other bio-based polymers.

Cradle-to-gate comparisons are common in the literature on bio-based polymers; however, they are of limited use for making comparative assertions because, often, the materials are not functionally equivalent. Nor do they include other parts of the life cycle, which may have significant contributions. Nevertheless, they can provide data for future cradle-to-grave studies, and if the environmental performance at a materials level is not attractive, there is a good chance that it will not be attractive at the product level either (Patel 2005).

2.2 Scope

2.2.1 Function

The function of the system investigated was production of a thermoplastic that can extruded and injection moulded into useful products, as a replacement for petroleum-based polymers such as polyethylene. Laboratory-produced NTP has comparable mechanical properties to linear low-density polyethylene (LDPE) and, hence, can be considered functionally equivalent to PE in many applications (Verbeek and van den Berg 2011).

A block flow diagram for the proposed large-scale thermoplastic modification of blood meal is shown in Fig. 1. In a patented process, blood meal is first mixed with reducing

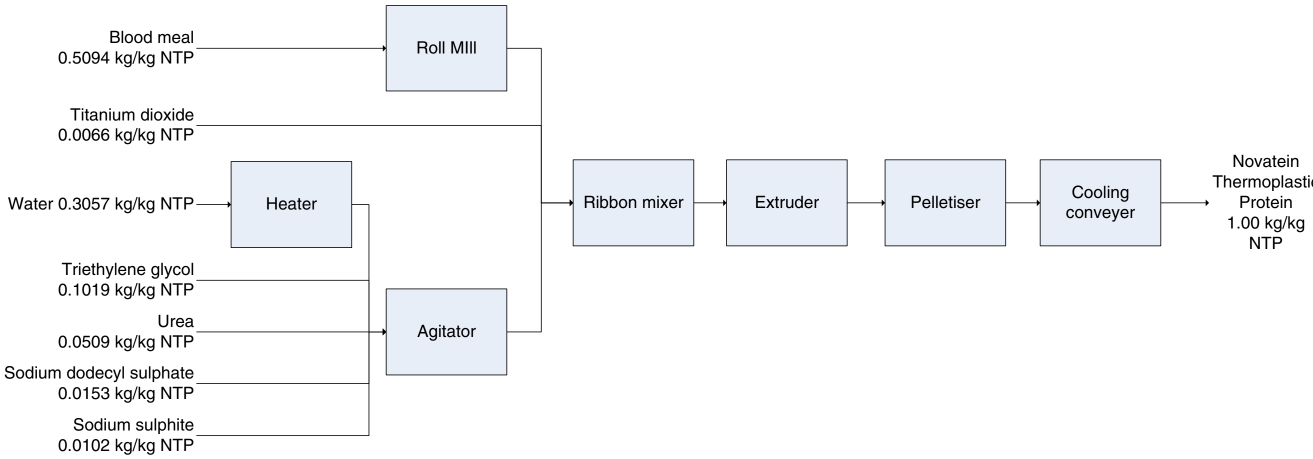


Fig. 1 Proposed commercial process for the production of NTP

agents, protein denaturants, and plasticizers that disrupt the interactions between the polymers (Verbeek et al. 2007). This increases chain mobility at lower temperatures, allowing thermoplastic extrusion. In the proposed large-scale process, water is heated by a gas heater and mixed with the denaturants and plasticizers in an agitator. This solution is added to the milled blood meal and mixed in a ribbon mixer before being fed through an extruder. The extruded polymer is pelletized and cooled before packaging.

2.2.2 System boundaries

This study was restricted to the cradle-to-gate portion of the life cycle as shown in Fig. 2. Delivered energy requirements were converted to NRPE. Capital costs were not included. Part 1 covered blood meal supply, and Part 2 covers blood meal conversion to NTP.

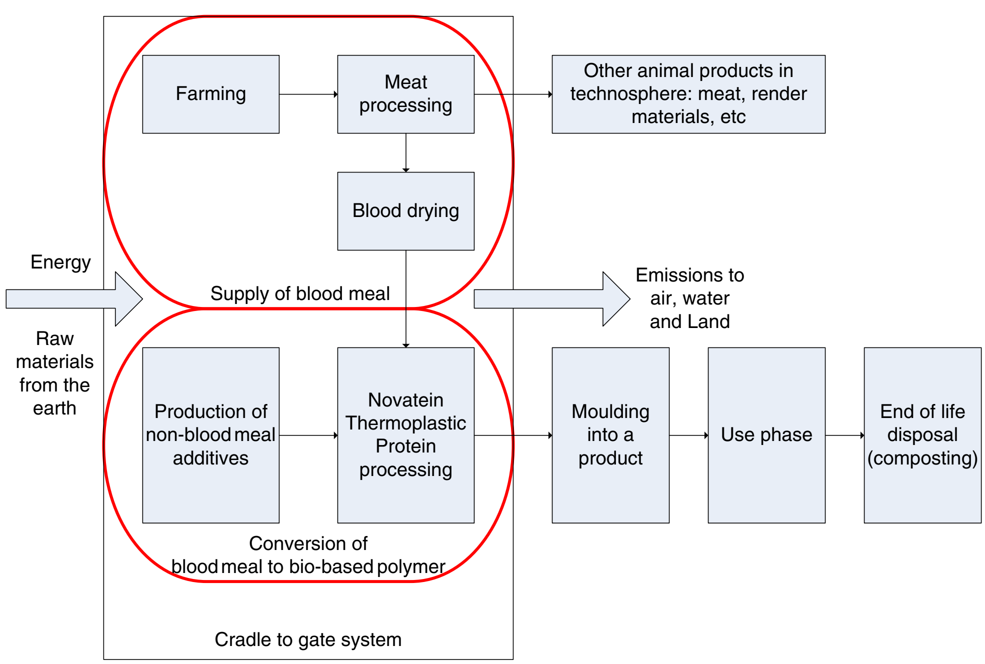
2.3 Data collection

Data collection for the supply of blood meal was discussed in Part 1, along with assumptions about electricity and the conversion of process energy to primary energy and emissions.

Process energy and raw material requirements for NTP processing were based on an engineering model constructed as part of a commercial feasibility study conducted internally for Novatein Limited (Smits et al. 2008).

Delivered energy requirements were converted to NRPE and GHGs using the coefficients for NZ available from

Fig. 2 Life cycle of NTP showing division of cradle to gate into production of blood meal and thermoplastic modification



Agrilink (Barber 2009). These were chosen because they are NZ specific and consistent with the source of data on farming and meat processing used in Part 1 (Barber et al. 2007).

Cradle-to-gate data on non-blood meal additives was obtained from a variety of sources:

- Primary energy and greenhouse emissions for production of urea at Kapuni in NZ have been estimated from previous studies (Wells 2001). This was chosen because it was NZ specific and, again, consistent with the source of data of farming and meat processing.
- Data on plant-based sodium dodecyl sulfate (SDS) was obtained from a cradle-to-gate study on PHA production systems (Akiyama et al. 2003). Petroleum-based SDS was also considered as an alternative (Patel et al. 1999).
- Sodium sulfite production was modeled using data from the European Commission for the Inorganic Chemical Industry (European Commission 2007), supplemented with data from the literature (Kim and Overcash 2003).
- Production of titanium dioxide was based on a worst-case scenario presented in the literature by a combined assumption that energy was entirely provided by coal (Reck and Richards 1999).
- Inventory on triethylene glycol (TEG) was based on data on ethylene glycol, adjusted to consider the different molar ratios of reactant to product (Patel 2003b).

A full description of the calculations used herein is available in a Master of Science thesis (Bier 2010)

2.4 Assumptions, choices and simplifications

2.4.1 Water usage

The proposed facility is located in the Taranaki region (NZ) where water is abundant. Primary energy for NZ reticulated water was used to account for the energy associated with supplying water to the NTP facility (Alcorn and Wood 1998). A full water footprint was beyond the scope of this study; however, the additional energy associated with supply of clean water in water scarce regions was considered in the sensitivity analysis.

2.4.2 Electricity

The average NZ electricity generation mix in 2008 (65% renewable, 35% nonrenewable) has been assumed as the default for blood drying and NTP processing (Barber 2009). A marginal electricity assumption using coal-fired electricity generation was also considered (100% nonrenewable). In this case, coefficients were adapted to coal-fired electricity production data for 2008 (Ministry of Economic Development 2009). For international electricity in the production of non-blood meal ingredients, coal-fired generation was also assumed, unless the data were already in the form of impact results when obtained.

2.4.3 Fugitive emissions

The main source of GHGs in the NTP processing unit process is in the production and delivery of process energy. Additionally, volatiles are released when blood meal is processed with chemical denaturants and extruded.

Fugitive emissions have previously been estimated at approximately 2% of mass flow for liquids of boiling point 20°C–60°C at 1 atm, 1% for liquids of boiling point 60°C–120°C at 1 atm, and 0.5% gases (Jiménez-González et al. 2000). The source of volatile organic compounds is decomposition of blood meal (a solid powder), and based on earlier recommendations, fugitive gases were estimated to be 0.5% of the mass of blood meal used. Emissions are volatile organic compounds with a global warming potential of 3.4 kg CO_2e/kg of volatile organic compounds (Forster et al. 2007).

2.4.4 Allocation

Following the discussion in Part 1, three allocation scenarios were chosen for investigation of the cradle-to-gate system. Additionally, for one allocation scenario (mass excluding waste and losses), two electricity generation assumptions have been included. The result is four NTP cases:

Case A: The impacts of farming and meat processing have been allocated based on the mass of raw blood.

Case B: The recoverable solids content of blood is assumed to be a coproduct of farming and meat processing, with the liquid fraction assumed to be a waste. Mass allocation is used between coproducts. This simulates a situation in which the demand for NTP is greater than the supply of blood meal.

Case C: The same allocation as situation B, but with electricity for rendering activities and NTP processing assumed to be supplied by coal-fired generation.

Case D: Low value by-product assumption, with no impacts of farming or meat processing allocated to blood meal. This simulates the situation in which blood meal supply is dependent on the demand for meat products and is in excess of the amount needed to produce NTP.

2.4.5 Impact assessment

The objective of this study was to assess NRPE and GHGs without considering other environmental impacts. Primary energy and energy-related GHGs were calculated using the coefficients for NZ published by Agrilink (Barber 2009). For nonenergy emissions, global warming potentials from

the Intergovernmental Panel on Climate Change were used (Forster et al. 2007).

2.4.6 Comparisons

NRPE use and GHGs for the cradle-to-gate portion of the NTP life cycle have been aggregated into three parts for comparison with other bio-based polymers such as PLA, PHAs, and thermoplastic starch (TPS):

- Production of biomass (including transport)
- Production of other additives (including transport)
- Production of polymer from the above materials

Initial comparisons were made on a cradle-to-gate basis for the production of 1 kg of polymer. This is not a true life-cycle assessment comparison of functionally equivalent systems. The various bio-based polymers considered have differing material properties and, therefore, are not necessarily functionally equivalent. Additionally, decisions and assumptions made when performing LCA in published systems vary. As such, although an interesting benchmark, the comparisons included here cannot be used to assert superiority of any of these materials over the others. To do so would require analysis of a complete product system from cradle to grave with consistent methodologies. A cradle-to-gate comparison is, however, a common first benchmark in studies on producing bio-based polymers (Akiyama et al. 2003; Kim and Dale 2005; Kim and Dale 2008; Vink et al. 2003).

3 Results

3.1 Blood meal supply

The effect of different allocation scenarios on NRPE use and GHGs associated with blood meal production was discussed in Part 1. Results for the allocation cases described above are shown in Tables 1 and 2.

3.2 Thermoplastic modification of blood meal to NTP

Results of the modification of supplied blood meal into NTP are shown in Table 3. It can be seen that the largest contribution to NRPE and GHGs in the conversion of blood meal into thermoplastic is the manufacture of TEG used as a plasticizer. It should be noted that urea and TEG both impart some "feedstock energy," representing the calorific value of nonrenewable materials normally used as fuel but, in this case, incorporated into the material. SDS has negative net emissions due to the uptake of carbon dioxide in plant feedstock growth exceeding the global warming potential of emissions during the manufacture (Akiyama et al. 2003).

Cradle-to-gate results for the above cases are summarized in Table 4, with categories used for comparison with other bioplastics.

4 Discussion

4.1 Sensitivity analysis

The following factors in blood meal conversion into NTP were investigated:

- Exclusion of plasticizer
- Data source for plasticizer
- Coal-fired electricity generation
- Low rainfall water supply
- Omission of titanium dioxide
- Petroleum-based SDS

The effect of these factors on nonrenewable energy use and GHGs for supplying non-blood meal additives and producing NTP is shown in Table 5. Blood meal supply was excluded to allow for a sensitivity analysis independent of the allocation method for farming and meat processing (see Fig. 2).

To check the effect of excluding the plasticizer (TEG), the formulation from the commercial feasibility study was used (Smits et al. 2008) and the mass fractions of the remaining components were recalculated (Table 6). The parts per hundred blood meal remained unchanged from the reference case recipe (Table 7), but the mass fractions of the other ingredients have increased.

The unplasticized formulation requires 55% less NRPE and 45% less GHGs from this portion of the life cycle compared with the reference case (see Table 5).

Table 1 Summary of NRPE for blood meal production in selected allocation cases

NRPE (MJ/kg NTP)	Case A	Case B	Case C	Case D
Blood drying	13.2	13.2	16.1	13.2
Farming	18.5	3.3	3.3	0.0
Meat processing	5.4	1.0	1.0	0.0
Biogenic carbon content	NA	NA	NA	NA
Transport of animals, blood and blood meal	0.9	0.6	0.6	0.5
Total	37.9	18.1	21.0	13.7

NA, not applicable

Table 2 Summary of GHGs (in kg CO_2e/kg NTP) for blood meal production in selected allocation cases

GHG (kg CO_2e/kg NTP)	Case A	Case B	Case C	Case D
Blood drying	0.8	0.8	1.1	0.8
Farming	13.5	2.4	2.4	0.0
Meat processing	0.2	0.04	0.04	0.0
Biogenic carbon content	−1.0	−1.0	−1.0	−1.0
Transport of animals, blood, and blood meal	0.1	0.04	0.04	0.04
Total	13.5	2.3	2.6	−0.2

Although such a reduction would seem beneficial, without additional plasticizers, the polymer may become brittle and unsuitable for its function when moisture is lost to the environment. The plasticized and unplasticized formulations are therefore not necessarily functionally equivalent. It may, however, be possible to use alternative plasticizers with a lower embodied energy. Further work is needed to test compatibility as well as evaluation on environmental criteria.

Sensitivity to the selection of data source for plasticizer was also considered. Ethylene glycol, diethylene glycol, and TEG are coproducts of the same process. Calculation of inventory for diethylene glycol based on data for ethylene (Hischier et al. 2005) and downstream refinery processes (Capello et al. 2009) resulted in 12% higher NRPE use for plasticizer production than that calculated using the molar ratio adjustment and data source used above for TEG. That same percentage change has been assumed for both NRPE use and GHGs in the production of TEG to determine the significance of uncertainty in the plasticizer data. This change had no significant effect on nonrenewable energy use or GHGs for the modification of blood meal to NTP.

Table 3 Results for modification of supplied blood meal to 1 kg NTP

Unit process	Nonrenewable energy use			GHGs (kg CO_2eq)
	Feedstock (MJ)	Process (MJ)	Total (MJ)	
NTP processing	NA	1.2	1.2	0.08
Process energy	NA	NA	NA	0.01
Direct emissions	NA	1.2	1.2	0.09
Non-blood meal additives	0	0.0	0.0	0.00
Water supply	0.8	0.8	1.5	0.08
Urea manufacture	0.0	0.4	0.4	0.00
SDS	0.0	0.2	0.2	0.02
Sodium sulfite manufacture	2.1	3.3	5.5	0.21
TEG manufacture	0.0	0.7	0.7	0.07
Titanium dioxide manufacture	NA	0.6	0.6	0.04
Transport of non-blood meal additives	2.9	6.0	8.9	0.40
Total for thermoplastic modification	2.9	7.2	10.1	0.49

Sensitivity to impacts from water supply (which, in the reference case, was negligible) was investigated by using primary energy and GHGs for desalinated water (Stokes and Horvath 2009). Although the alternative data were for California, rather than NZ, this was used as a worst-case estimate representative of water supply in areas where clean, fresh water is scarce. The variance was not significant (see Table 5).

Both the most energy intensive manufacturing method and the most greenhouse gas causing energy supply have been assumed for producing titanium dioxide in the reference case. Under that assumption, titanium oxide's contribution to both impact categories is more than SDS and sodium sulfite combined. Titanium oxide was added as a pigment and tracer for laboratory analysis but is not always necessary for thermoplastic processing and could be omitted in commercial production. NRPE use and emissions omitting titanium oxide for the formulation in Table 7 is shown in Table 5.

Despite the high NRPE and GHGs assumed for titanium dioxide, the mass fraction within NTP is so small that the variance in NRPE is not significant. Omission of titanium dioxide does, however, reduce GHGs in this portion of the life cycle by 13%.

In the reference case, SDS is manufactured from plant-based feedstock and includes a net reduction in greenhouse gases on a cradle-to-gate basis due to its biogenic carbon content. This assumption was investigated by replacing energy and emissions data with those for production of anionic alcohol sulfate surfactants from petroleum-based feedstock in Germany (Patel et al. 1999). This change does not significantly affect NRPE use or GHGs for the supply of non-blood meal additives and processing into NTP compared with the reference case.

It should be noted that the variance of all alternatives was will be smaller in the cradle-to-gate system when the supply of blood meal is also included in the impact assessment.

4.2 Comparison with other bio-based polymers and relative contributions of life cycle phases

Nonrenewable energy use and GHGs for NTP production were compared with those of systems that produce TPS, PLA, and PHA. The case for TPS was a cradle-to-gate plus grave assessment, which included incineration at the end of life (Patel 2005). For PLA, two sets of data were obtained, one based on engineering estimates and a more recent assessment based on actual plant information. These PLA assessments included results with wind power credits to

Table 4 NRPE use and net GHGs for cases A, B, C, and D

	NRPE use (MJ/kg)				GHGs (kg CO_2e/kg)			
	A	B	C	D	A	B	C	D
Supply of blood meal	37.9	18.1	21.0	13.7	13.5	2.3	2.6	−0.2
Supply of non-blood meal additives	8.89	8.89	8.89	8.89	0.40	0.40	0.40	0.40
NTP processing	8.9	8.9	8.9	8.9	0.4	0.4	0.4	0.4
Total	1.2	1.2	3.1	1.2	0.08	0.08	0.3	0.08

reduce nonrenewable energy use and emissions associated with electricity production (Vink et al. 2007; Vink et al. 2003). This is not usually done in LCA or carbon footprinting studies and is specifically excluded from carbon footprinting in the PAS 2050 (British Standards Institution 2008). Nevertheless, the NZ context of NTP already includes a significant portion of renewable electricity, so comparison with a PLA system using renewable electricity is of interest. PLA results with and without the credits have both been compared with NTP. For PHA, three cases were considered. The first two cases used conventional energy, but different feedstocks (corn and soy) (Akiyama et al. 2003). The third case used corn as feedstock and renewable energy (Akiyama et al. 2003; Kim and Dale 2008). Figure 3 shows NRPE use for the four NTP scenarios and those other bio-based polymer systems. Where available, nonrenewable energy data have been split into the same sections of the life cycle as used for NTP; otherwise, only the total has been included.

Process energy for the conversion of biomass to bio-based polymer only has a small contribution to the ecoprofile of NTP. This is in contrast to fermentation-based polymers such as PLA and PHA, for which this makes up approximately half the cradle-to-gate nonrenewable energy demand when conventional energy is used.

Figure 4 shows net GHGs for the same cases. In cases A, B, and C, with allocation of impacts from farming on a mass basis, the amount of emission calculated is greater than that reported for other bio-based polymers. In case A, the total emissions attributed to NTP are approximately an order of magnitude greater than the other bio-based polymer systems considered. In contrast to plant-based biomass, the upstream production of animal biomass from ruminants produces more emissions than it absorbs. Inclusion of these on a mass allocation bases dwarfs emissions from other unit processes in the production of NTP.

In case D, the impacts of farming and meat processing are allocated entirely to main products and not to blood or blood meal. In this case, emissions are comparable with those reported for PHA with conventional energy and less than those reported for PLA using conventional energy. Due to the uncertainty involved in performing an LCA and potential for different decisions in each system, this does not necessarily mean that NTP produces fewer emissions per kilogram than PLA. Nonetheless, the relatively low process energy for conversion of blood meal to NTP and NZ's high proportion of low-emission renewable electricity generation would suggest that this is the case.

For the case of TPS, emissions from incineration at the end of the material's life were included. This releases any biogenic carbon content back into the atmosphere. Omitting the negative contribution to net GHGs of NTP to allow for a more appropriate comparison with the TPS case adds an additional 1.0 kg CO_2e/kg NTP to each NTP case. This pushes emissions for even the lowest case (case D) higher than those shown for TPS in Fig. 4 (1.3 kg CO_2e/kg NTP vs. 1.1 kg CO_2e/kg TPS).

The bio-based polymers discussed above may have different material properties and, therefore, are not necessarily functionally equivalent. Additionally, decisions and assumptions made when performing LCA in these systems varied. As such, although an interesting benchmark, these

Table 5 Sensitivity analysis for the conversion of blood meal to NTP (excluding blood meal supply)

New assumption	NRPE (MJ/kg NTP)	Variance from base	GHGs (kg CO_2e/kg NTP)	Variance from base
Reference (Table 3)	10.1	0%	0.49	0%
Exclusion of plasticizer	4.49	−55%	0.27	−45%
Alternative data source for plasticizer	4.5	−55%	0.27	−45%
Coal-fired electricity generation mix	11.95	19%	0.71	45%
Low rainfall water supply	10.7	7%	0.51	5%
Omission of titanium dioxide	9.38	−7%	0.42	−13%
Petroleum-based SDS	12.0	19%	0.71	45%

Table 6 Composition of NTP without TEG as a plasticizer

Material	Mass fraction (kg/kg NTP)	Parts per hundred blood meal (pph_{BM})
Water	0.340	60
Urea	0.057	10
SDS	0.017	3
Sodium sulfite	0.011	2
Titanium dioxide	0.008	1.3
Blood meal	0.567	100
NTP	1	176.3

comparisons cannot be used to assert superiority of any of these materials over the others. Nevertheless, they confirm that the energy used in producing NTP is in the same range as that used in producing other bio-based polymers. Additionally, it is highlighted that different systems, system boundaries, allocation procedures, and assumptions about energy affect the apparent cradle-to-gate ranking of bio-based polymers. This should be taken into account when expanding analysis of these materials to a full cradle-to-grave analysis. Furthermore, the comparisons here identify different hotspots, contributing most to NRPE and GHGs, in the production of different bio-based polymers. This may imply that different strategies are required for the improvement of these processes with regard to reducing environmental impacts.

In general, the energy and emissions calculated for modification of blood meal into NTP are lower than those reported for manufacturing other bio-based polymers. It is only when the impacts of farming, meat processing, and blood meal supply are included that NTP appears less favorable.

It is interesting to note that under the attributional scenarios considered, biomass production had the largest contribution to the impacts of producing NTP. This is counterintuitive for a second-generation bioplastic, where the motivation was to develop a material using a by-product of an existing system. While Part 1 discussed the allocation problem in more detail, this serves to highlight a limitation of a purely attributional approach. Such an approach does not take into account that a portion of the life cycle with comparatively large impact is an existing process, the volume of which is driven by the demand for meat. In contrast, a consequential approach would allow for the prior existence of the upstream processes that produce blood meal. In particular, the change in impact from using blood meal as a fertilizer to using blood meal as a feedstock for plastics could be evaluated.

Table 7 Composition of NTP without titanium dioxide

Material	Mass fraction (kg/kg NTP)	Parts per hundred blood meal (pph_{BM})
Water	0.308	60
Urea	0.051	10
SDS	0.015	3
Sodium sulfite	0.010	2
Triethylene glycol	0.103	20
Titanium dioxide	0.000	0
Blood meal	0.513	100
NTP	1	195

4.3 Comparison with producing petroleum-based polymers

The motivation for producing bio-based polymers is to replace conventional polymers. Therefore, while a comparison with other bio-based polymers provides a valuable benchmark, it is also important to consider the petroleum-based polymers NTP could replace. The material properties of NTP are similar to LDPE, and these are therefore functionally equivalent in some applications (Verbeek and van den Berg 2011).

In case B, NTP production uses 28 MJ/kg NRPE, of which 3 MJ/kg represents the use of nonrenewable feedstocks. The remaining 25 MJ/kg is for process energy supply. LDPE uses 72 MJ/kg NRPE, of which 49 MJ/kg represents the use of nonrenewable feedstocks (PlasticsEurope 2008). If, at the end of its life, polyethylene is incinerated, some of this can be recovered. This leaves 24 MJ/kg as being for process energy supply during manufacture. The amount of energy used, excluding the use of nonrenewable feedstocks, is therefore about the same for both materials. NTP production has an estimated net of 2.8 kg CO_2e/kg of GHG, more than the 1.9 kg CO_2e/kg of LDPE. On this comparison, NTP as a replacement for LDPE is justified as a way to reduce dependence on nonrenewable feedstocks, but not as way of reducing GHGs.

Under an alternative scenario, as explored in case D where no impacts of farming and meat processing are allocated to blood, the NTP production emits 0.3 kg CO_2e/kg. This is less than that emitted in producing an equivalent amount of polyethylene. If the demand for blood meal to produce NTP can be met by existing farming activities, such a scenario is justified. Therefore, replacement of LDPE with NTP may contribute to a reduction in emissions. A full cradle-to-grave system would still be required to confirm this for specific products and end-of-life disposal methods.

The weathering and degradability properties of NTP are not the same as LDPE. This means that there are applications that LDPE is suitable for, for which NTP would not be a suitable replacement. The converse of this is that NTP may be disposed of by methods at the end of its useful life that are not open to polyethylene (e.g., composting).

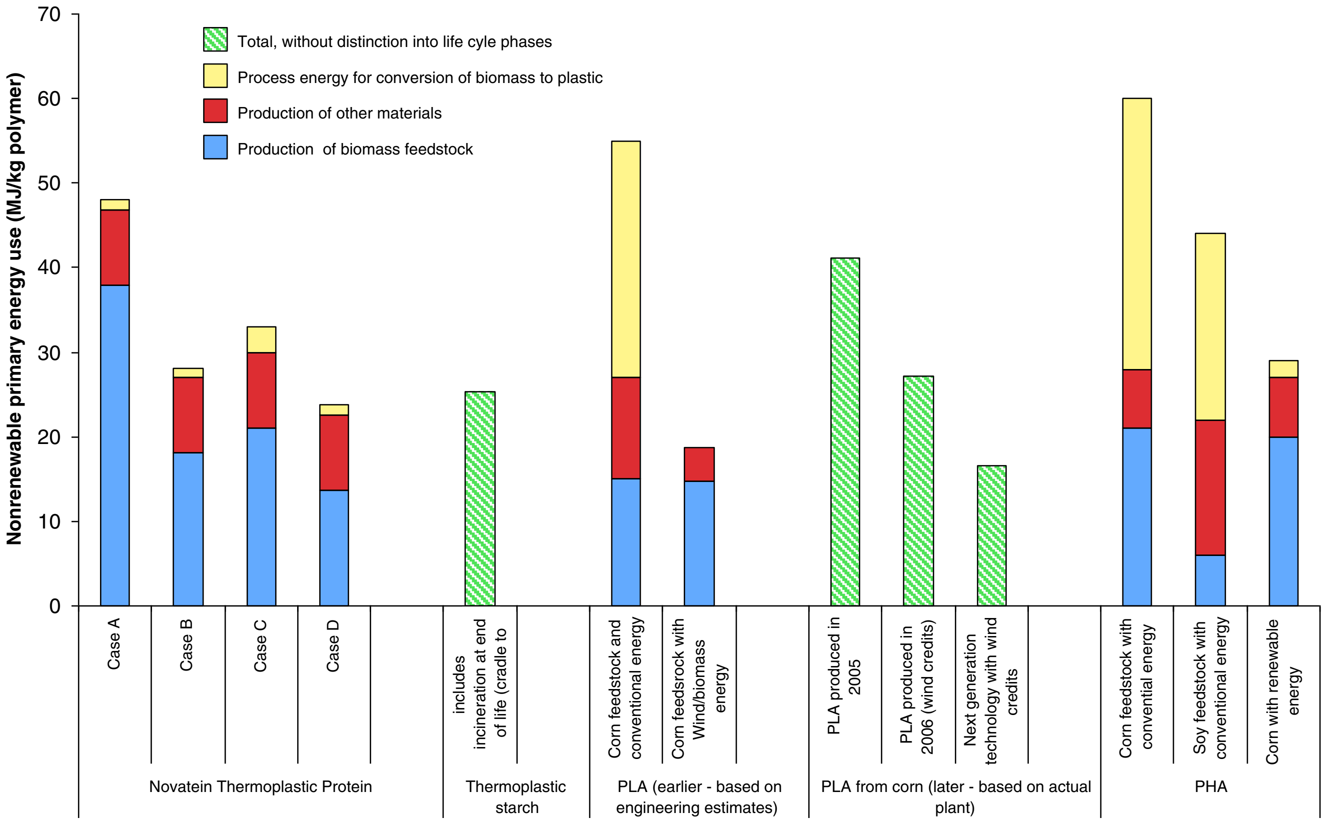


Fig. 3 Cradle-to-gate NRPE for NTP and other bio-based polymers

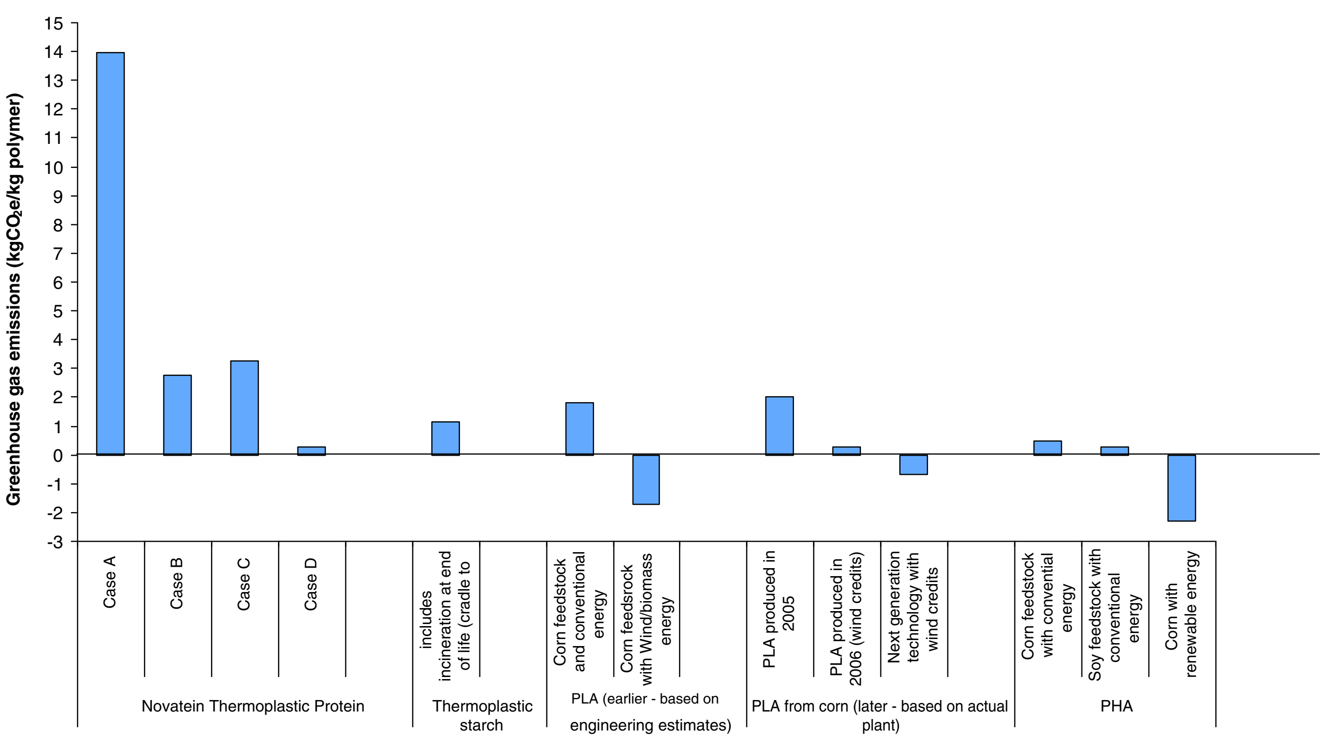


Fig. 4 Cradle-to-gate GHGs for NTP and other bio-based polymers

4.4 Limitations

4.4.1 Impact categories

This assessment was limited to nonrenewable energy use and GHGs. Although not a complete picture, these are sometimes correlated with other impacts (Huijbregts et al. 2005; Pietrini et al. 2007). This is not always the case; specifically, in the primary sector, other impacts such as land use, water use, and eutrophication may be significant without being directly related to the combustion of fossil fuels sources. It would be reasonable to predict that such impacts, which are strongly associated with agriculture, would be subject to the same allocation difficulties as agricultural emissions. That is, depending on the allocation scenario applied, they will either dominate or be minimal in the profile for NTP. The impacts of NRPE and GHG are the main motivators for the production of bio-based plastics. Although some systems show improvements in these two categories when compared with petroleum-based polymers, the conclusion that they are better may be less evident if additional categories were also considered.

4.4.2 Scope

This inventory and impact assessment is limited in that it only considers NTP production and not its use to fulfill a function as a material or any additional functions possible in end-of-life disposal.

Within the cradle-to-gate system, upstream production of blood meal has a significant contribution to nonrenewable energy use and GHGs. It is anticipated that at the end of its life, NTP will be disposed of via composting to create nitrogen-rich compost. If the same fertilizing activity as standard blood meal can be achieved after use as a plastic, a system expansion without the need for synthetic fertilizers can be considered. For example, the following two systems could be compared from cradle to grave:

- Blood meal used as fertilizer.
- Blood meal used to make NTP, displacing a petroleum polymer, then used as a fertilizer at the end of its life

The impacts of farming, meat processing, and blood drying will be common to both systems. When evaluating the difference in environmental consequences between them, it is not necessary to quantify impacts from shared upstream unit processes. Including this additional function on a cradle-to-grave basis could therefore eliminate the allocation problem for NTP. The result is that none of the impacts for producing blood meal would need to be included in the comparison between NTP and other polymers in such a cradle-to-grave scenario. The NRPE and GHGs associated with the production of NTP in such a system would then be 10 MJ/kg and 0.5 kg CO_2e/kg, respectively.

5 Conclusions

The objectives of this assessment were the estimation of cradle-to-gate nonrenewable energy use and GHGs that can be attributed to NTP, identification of the largest contributions to that energy demand, and those emissions and comparison with other bio-based polymers.

The reference scenario, case B, using a mass-based allocation for impacts of farming and meat processing, attributed 28 MJ NRPE and 2.8 kg CO_2e to producing 1 kg NTP. Within the reference scenario, blood meal production accounts for more than half of the NRPE use and GHGs on a cradle-to-gate basis. With NRPE, it is blood drying that contributes the most, accounting for 47% of the total for the system.

An alternate scenario can be considered in which blood is seen as a waste and not allocated any of the impacts of farming and meat processing. Under such a system, 24 MJ NRPE and 0.3 kg CO_2e are attributable to NTP production. In this scenario, blood drying has the greatest contribution to nonrenewable energy use. Fuel combustion to supply this energy becomes the greatest contribution to GHGs in this system.

Emissions per kilogram of polymer in the reference system are greater than those for other bio-based polymers or conventional polymers obtained from the literature. In case D, where whole blood is deemed a waste with respect to farming and meat processing, emissions are less than for the production of PLA or TPS using conventional energy, but still higher than the net emissions for the PLA or PHA production systems, which make use of renewable energy in fermentation and recovery processes.

Impacts associated with the supply of energy for the conversion of biomass to bio-based polymer are only a small part of the overall contribution to environmental impacts for NTP. This is in contrast to fermentation-based polymers, in which energy use in fermentation and recovery can account for greater than 50% of the impacts with regard to nonrenewable energy use and greenhouse gases. In the reference scenario and the alternate scenarios, however, the total cradle-to-gate NRPE use is of a similar order of magnitude to production of other bio-based polymers. With emissions, it is farming that has the largest contribution, with 88% of the net emissions.

This study only considered GHGs and nonrenewable energy use. These are not the only impact categories relevant to agricultural products, and future work with the NTP system should extend the analysis to a broader range of categories, including eutrophication and water usage. Additionally, future work should consider the full product life cycle of a function fulfilled with NTP. A consequential LCA could compare the existing use of blood meal as fertilizer with its conversion to plastic to displace functions fulfilled by petroleum-derived polymers.

Together, Parts 1 and 2 of this study have demonstrated that for systems that make use of low-value by-products, the choice of allocation scenario may be incredibly significant. As such, any allocation procedures used should be presented transparently and with consideration of alternatives.

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